High-Frequency Acoustic Propagation in Shallow, Energetic, Highly-Salt-Stratified Environments

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LONG-TERM GOALS

The long term goal of this research is to measure and understand high-frequency, line-of-sight acoustic propagation in an estuarine environment characterized by strong tidal flow, often large salinity stratification, high shear, high dissipation rates of turbulent kinetic energy, shear instabilities, and increased water property variability.

OBJECTIVES

Acoustic propagation techniques provide a means for remote-sensing of the path-averaged statistical structure and motion of the intervening flow, providing information on the 2-dimensional characteristics of turbulence, microstructure, and advection. Estuaries provide an excellent environment to quantify stratified turbulence and its influence on acoustic propagation as a broad range of stratification and turbulence intensities are encountered within a single tidal cycle.

The primary objective was to conduct high-frequency (120 kHz), line-of-sight acoustic propagation measurements in the Connecticut (CT) River estuary. These measurements were successfully conducted from 4-9 December 2012. In addition, measurements of high-frequency broadband acoustic backscattering (120 – 600 kHz), currents (using a 1.2 MHz ADCP), suspended sediment concentrations, fluorescence, and continuous conductivity, temperature, and depth (CTD) measurements were performed in order to support the interpretation of the scintillation data. Simultaneous microstructure measurements were also conducted at various depths throughout the water-column on 6-7 December 2012.

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Secondary objectives of this study include 1) testing the validity of the existing theoretical framework for propagation of high-frequency sound through a highly turbulent medium, 2) determining the range of conditions under which the existing theoretical framework is accurate, 3) quantifying the effects of turbulence anisotropy on the effective refractive index fluctuations, which are related to turbulence parameters, and 4) understanding the influence of coherent 3-D wave structures and shear instabilities on high frequency acoustic propagation in highly sheared, high-Reynolds number environments.

APPROACH

Decades of research has shown that the propagation of sound waves through a moving random medium, such as the atmosphere [1] or the ocean [2], provides a means for remote-sensing of the path-averaged statistical structure and motion of the intervening fluid medium. These techniques, however, have been less exploited at high acoustic frequencies and over short ranges, applicable in shallow coastal waters, where there can be highly variable fluid flows, with intermittent strong mixing and high stratification, depending on the tidal cycle, wind, currents, and topography. Under these conditions, it is typical to encounter regimes of homogenous and isotropic turbulence, and for propagations distances over which the Rytov approximation holds, it is possible to infer path-averaged turbulence parameters using Tatarski's weak scattering theory. Though there have been a number of theoretical and numerical studies [e.g. 3, 4] that apply these techniques to investigating turbulence in shallow waters, and its influence on acoustic propagation, there have only been a handful of measurements performed [e.g. 5-8], with a focus on relatively unstratified conditions.

High-frequency, line-of-sight acoustic scintillation measurements have been performed in the CT River estuary (Figure 1). This highly-salt-stratified estuarine environment should provide the framework for a better understanding the complex problem of high-frequency sound propagation in shallow, highly-stratified, highly-energetic environments, and for setting bounds on the range of validity of Tatarski's weak scattering theory. Quantifying and understanding the influence of turbulence on high-frequency acoustic propagation, for example quantifying the times scales of variability, is particularly important in the context of recent developments in the area of high-frequency, shallow-water, acoustic communications, as well as being particularly relevant to the development of acoustic observatories. Acoustic observatories provide a powerful remote-sensing technique for real-time long-time-series monitoring of transport, mixing, and circulation patterns in coastal regions. Measurements of turbulence and microstructure in the ocean are usually performed with high-spatial resolution instruments, such as ADVs, shear probes, or fast-response thermistors and conductivity sensors. However, these are time-consuming, point measurements, which can be influenced by local inhomogeneities and may not be representative of the mean flow. In contrast, high-frequency acoustic propagation techniques average over local anomalies along the transmission path and can provide information not only on path-averaged dissipation rates of turbulent kinetic energy but also on mean flows.

WORK COMPLETED

1. Scintillation System Hardware and Software Upgrades.

The scintillation system was originally deployed during the SPACE08 experiment. In the SPACE08 configuration, all electronics were located underwater on tripods. Significant hardware and software modifications were performed in order to allow the electronics to be updated and to ensure that the

electronics were no longer housed underwater on the tripods, allowing real-time visualization and immediate changes to transmit signals to be implemented in response to changing flow parameters. The transducers have also been replaced with high quality transducers and the cables have been made longer for shore- or vessel- based operations. In addition, new modular tripods have been constructed that allow easy transportation to the CT River field site and are robust enough to withstand the typical currents encountered in the CT River. The modifications to the scintillation system hardware and software have been performed by Ron Teichrob and Svein Vagle in Sidney, BC. Andone Lavery spent one week in British Columbia in June 2012 testing the system. Final system assembly and testing was performed at WHOI prior to the deployment December 2012.

2. Modeling and Logistics.
Two one-day reconnaissance trips to the CT River were undertaken in June 2011 and August 2012 to assess the best location for deployment of the scintillation system, balancing both the scientific needs and logistical difficulties, as well as to determine the influence of different discharge regimes on the observation of shear instabilities. Modeling of the acoustic propagation eigenrays based on the CTD data collected in the CT River was performed determine the best signals.

3. Permitting.
The Coast Guard, the Army Corps of Engineers, and the State of Connecticut Department of Energy and Environmental Protection (CT-DEEP) were contacted regarding permits and regulations. A Local Notice to Mariners was posted prior to the experiment, and navigation buoys were designed and purchased for compliance with CT-DEEP regulations.

4. Field Experiment.
The measurements were conducted from 4-9 December 2012 at a site approximately 500 m south of the Amtrak Railroad bridge (Figure 1) with the acoustics propagation/scintillation system cabled to the RV Connecticut, a 76 foot vessel with dynamic positioning, which served as a floating laboratory and was on-site for the duration of the experiment, allowing real-time data-collection and visualization. The system consists of two, 120-kHz, 4-transducer, $1 m^2$ square acoustic arrays mounted on tripods with the center of each array 3 m above the bottom (Figure 1). The tripods were separated by approximately 40 meters. The novel and key capability of this system is that every transducer has both transmitting and receiving capabilities, allowing forward and reciprocal acoustic transmissions along 16 different reciprocal paths. The field measurements encompassed multiple tidal cycles, with different degrees of turbulence intensities generated throughout any given tidal cycle.

A broadband acoustic backscattering system (120-600 kHz) was deployed 20 m south (downstream during the ebb tide) of the propagation path in order to provide information on microstructure [9] and structure of shear instabilities. In order to address questions relating the 3-D structure of the shear instabilities, the 6 broadband transducers that comprise the backscattering system were separated to span a 6 m array. A 1.2 MHz ADCP was also mounted on the backscattering array to measure velocity and to enable shear to be inferred, as well as a CTD (sampling at 16 Hz) and a fluorometer. Continuous vertical CTD profiles were also be performed in order to measure water column characteristics. Finally, depth resolved turbulence measurements were performed on 6-7 December 2012 using the Measurement Array for Sensing Turbulence [10] deployed from the WHOI coastal research vessel RV Tioga.

RESULTS

The primary result of this work is the successful completion of a high-frequency propagation experiment in a highly-stratified, shallow, and variable, estuarine environment. Initial analyses have revealed that this environment is strongly upwardly refracting (sound speed dominated by salinity and resulting in no discernible bottom interacting arrival) and variable, resulting in highly variable direct arrivals (Figure 2). The direct arrivals completely drop out during the flood tide when the velocity maximum associated to the incoming salt spans the depth of the array.

The ebb tide (red lines in Figure 2) is characterized by shear instabilities (Figure 3) and intense turbulence, which in turn results in highly fluctuating time of arrival and signal amplitude. Furthermore, there is initial evidence that individual shear instabilities can be identified in the time of arrival structure during the ebb tide (Figure 4), suggesting that the shear instabilities are coherent across the spatial scale set by the separation between the tripods, or approximately 40 m.

Future analyses will focus on:

- Extend the theory for log-amplitude and phase fluctuations in the inertial subrange to the viscous-convective and dissipation subranges appropriate for energetic and stratified environments.
- Perform ray-tracing to understand the influence of salt-stratification on the structure of the direct arrivals.
- Determine the range of validity of Tatarski's weak scattering theory from the acoustic scintillation.
- Use the two-dimensional angle of arrival fluctuations to determine the importance of anisotropy throughout the tidal structure.
- Investigate the influence of coherent 3-D wave structures and shear instabilities generated in highly sheared, high-Reynolds number environments.
- Invert the acoustic measurements to infer parameters associated to the 2-dimensional characteristics of turbulence, microstructure, and advection, when appropriate.

The following conference proceedings have resulted from this work:

- Lavery, A.C, Geyer, W.R, and Scully, M.E. "Quantification of stratified turbulence using acoustic propagation and broadband acoustic backscattering techniques," Proceedings of Meetings in Acoustics (POMA **19**, 005005, 2013. DOI: 10.1121/1.4798946
- Lavery, A.C. "High-frequency acoustic scattering and propagation techniques in highly-stratified shear flows: Useful tools for characterizing mixing?" (Invited Paper) Proceedings of the 1st International Conference and Exhibition on Underwater Acoustics, Corfu, Greece, 23-28 June, edited by J.S. Popodokis and Leif Bjorno: 1179-1186, 2013.

The following talks have resulted from this work:

- Lavery, A.C., "Acoustic scattering and propagation in strongly salt-stratified shear flow", University of Massachusetts Dartmouth, SMAST, MA, April 2013. (Invited)

- Lavery, A.C. “High-frequency acoustic scattering and propagation techniques in highly-stratified shear flows: Useful tools for characterizing mixing?” 1st International Conference and Exhibition on Underwater Acoustics, Corfu, Greece, June 2013. (Invited)
- Lavery, A.C., Geyer, W.R., Scully, M.E “Quantification of stratified turbulence using acoustic propagation and broadband scattering techniques” 165th Meeting of the Acoustical Society of America, Montreal, CA, June 2013. (Contributed)

IMPACT/APPLICATIONS

Increased understanding of high-frequency acoustic propagation in shallow estuarine environments characterized by strong tidal flow, high shear, strong stratification and dissipation, and increased water property variability. Assessment of the importance of anisotropy and 3-D structure of turbulence in determining acoustic propagation in these environments.

RELATED PROJECTS

None.

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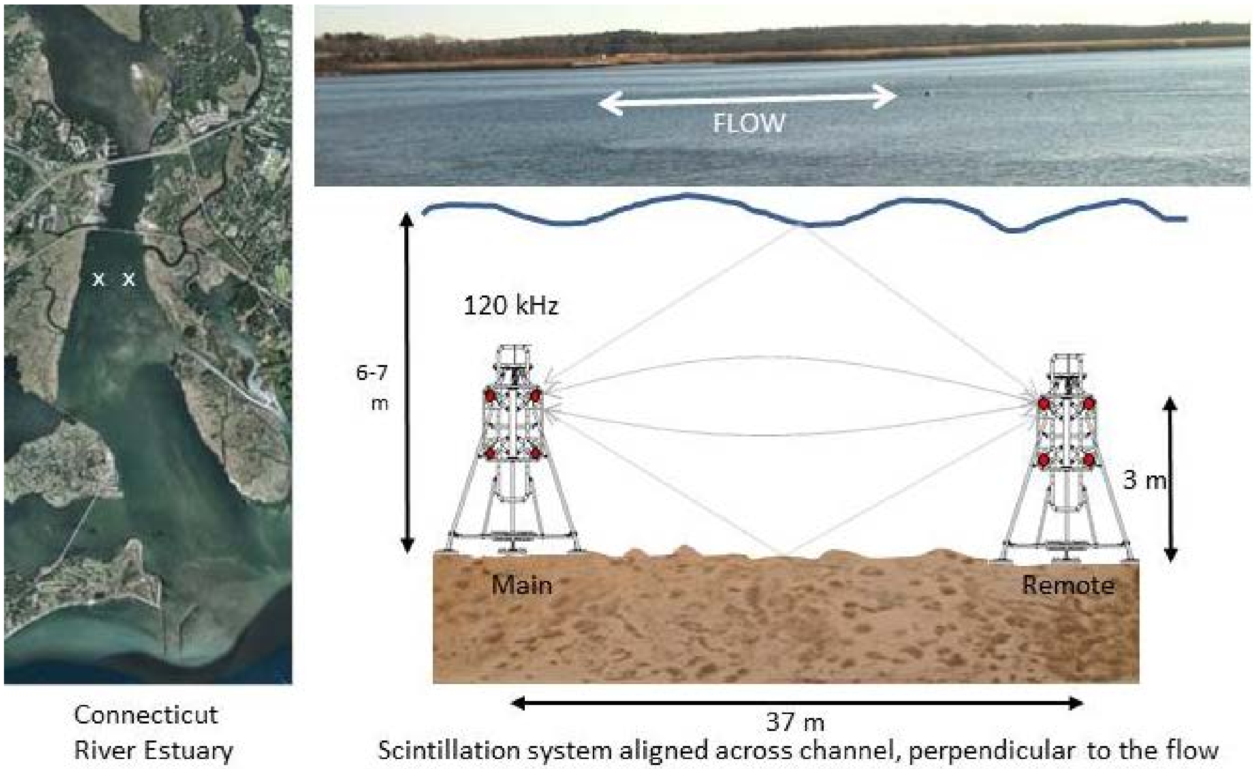

Figure 1. Google Earth map of the CT River estuary and positions of the two high-frequency acoustic propagation/scintillation arrays/tripods (left), photograph of the surface navigation buoys marking the location of the two tripods (top right), and a schematic of the estuary and the tripods (bottom right).

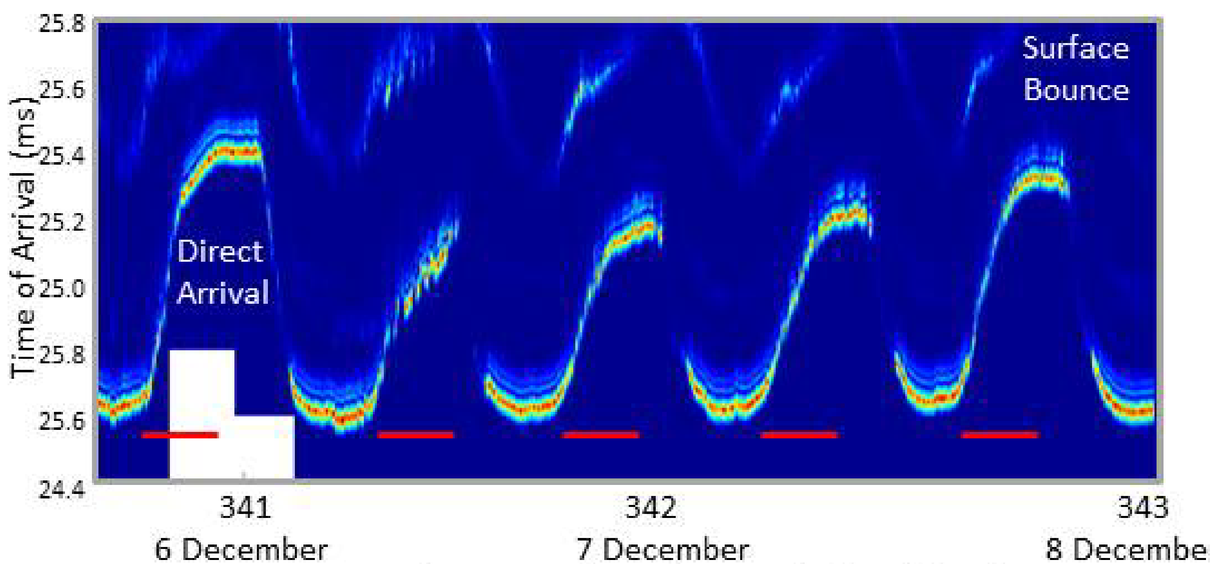

Figure 2. Time of arrival structure throughout multiple tidal cycles. The red lines indicate the ebb tides.

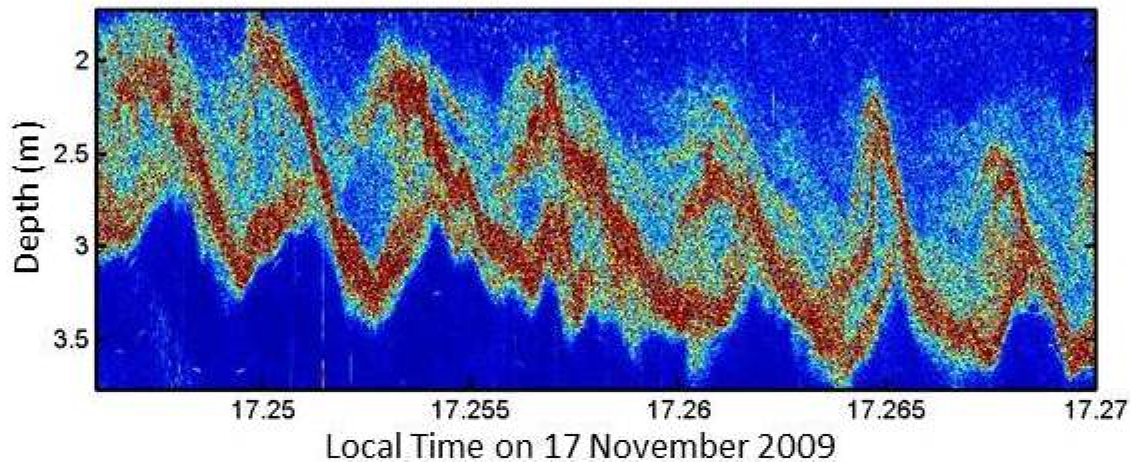

Figure 3. Typical shear instabilities observed in the CT River using broadband acoustic backscatter. The signature of shear instabilities was clearly observable in the time of arrival structure of the high-frequency acoustic propagation signals.

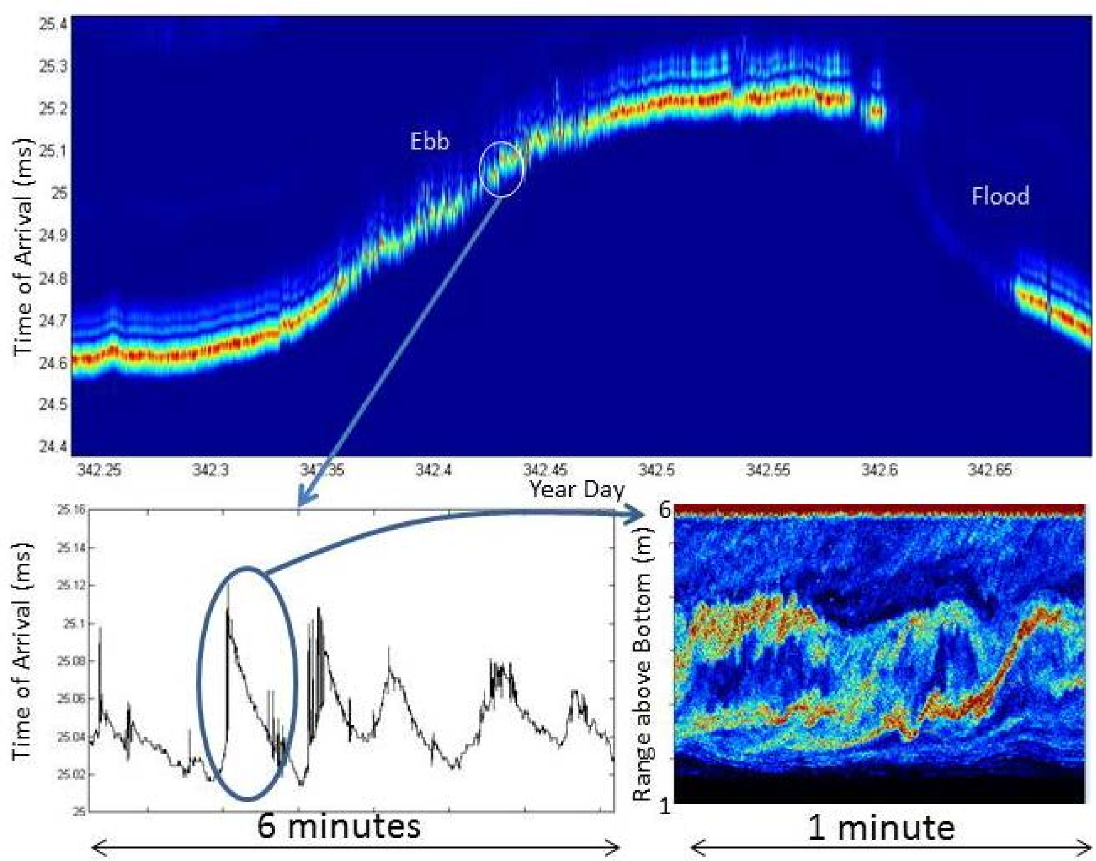

Figure 4. Top panel: Time of arrival structure throughout a single today cycle, illustrating high variability in both the amplitude and arrival time, particularly during the ebb tide, as well as the impact of the current velocity maximum during the flood tide, resulting in almost complete signal loss. Bottom left: Time of arrival structure during a period in which large shear instabilities were observed. Bottom right: Broadband (120-600 kHz) acoustic backscatter over the same time period as the time f arrival shown in the right hand panel, illustrating a large amplitude shear instability.